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Design and Implementation of a Web-Based Configuration Control System for Groundwater Circulation Well Equipment

Chang Su, Jun Liu*, Xiaofeng Yang

College of Nuclear Technology and Automation Engineering, Chengdu University of Technology, Chengdu, China
Email: *450730389@qq.com

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Abstract

With the acceleration of urbanization and the rapid development of modern agriculture, the quality of urban groundwater in China has deteriorated significantly, affecting regional economic and social development. Due to the concealed and harmful nature of groundwater pollution, remediation efforts are urgently needed. Despite some existing research in China, technical application experience is limited. This study aims to develop an intelligent control system for *in-situ* groundwater remediation technology. The research includes the development of proprietary dynamic visualization systems, remote control systems, decision support systems, and safety risk warning systems, as well as constructing an intelligent management control software platform for *in-situ* groundwater remediation equipment. The system is based on Modbus and Websocket protocols, establishing a real-time MySQL database for automatic data collection and storage. A web application is developed and deployed to the cloud platform, allowing visual remote inspection and management control through smart terminals. Experimental results show that the control system meets the requirements of groundwater remediation equipment, offering enhanced convenience compared to traditional industrial control systems. Cloud storage not only improves data security but also lays the foundation for future big data analysis and improved pollution control outcomes.

Subject Areas

Nuclear Chemistry

Keywords

Control System, Visualization, Cloud Platform, Groundwater Remediation

1. Introduction

Groundwater is a crucial source of drinking water in both urban areas and rural communities [1]. However, with the rapid pace of urbanization and changes in agricultural practices, groundwater quality in China has significantly deteriorated, posing severe threats to environmental health and human safety. This pollution primarily stems from industrial activities, extensive use of fertilizers and pesticides, and livestock farming [2], which introduce various contaminants, including heavy metals and organic compounds [3]. *In-situ* injection remediation technology has emerged as an effective environmental remediation method by injecting chemical or biological agents into contaminated groundwater or soil to significantly reduce pollutant concentrations [4], while causing minimal land damage [5]. Despite its effectiveness, this technology faces several challenges, such as the typically long duration required for remediation and the complexity of addressing multiple types of pollutants. Additionally, traditional control systems often rely on prolonged on-site monitoring by professionals, which is cumbersome and inefficient. Although recent advancements in web-based control systems have improved monitoring and management convenience [6], issues with technology integration, data security, and data analysis optimization still persist. These challenges highlight the need for continued research and development to enhance groundwater remediation technologies and systems, meeting the growing demands for environmental protection.

2. Design of Complete Control System

To comprehensively monitor and store data from all equipment at the site for subsequent analysis and processing, a comprehensive data acquisition module needs to be established. This module will be responsible for collecting real-time data from site equipment and ensuring data accuracy and integrity [7]. Additionally, a distributed storage module must be configured to efficiently and securely store all collected data, allowing for quick retrieval and use when needed. Moreover, to provide a more intuitive view of site data and process flow status, a visualization large-screen module should be included to display real-time data and process conditions. By utilizing web technology, users can access web pages anytime and anywhere, facilitating real-time data monitoring and management, thus enhancing data accessibility and system flexibility.

2.1. System Target

The web configuration software is primarily used to implement control functions and visually display the operating status of on-site equipment and changes in well parameters through the monitoring interface. Additionally, it includes features such as fault alarms and parameter settings. With the help of the web configuration system, users can remotely access the monitoring and control system via the Internet, eliminating the constraints of specific geographical locations. This means users can connect to the system at any time using various devices, such as computers, smartphones, and tablets, to monitor and control remote equipment in real-time. Furthermore, the web configuration system provides an intuitive user interface and customizable display panels, allowing users to easily monitor and accurately understand the operational processes and status of on-site equipment.

2.2. Functional Design

As the core system of the groundwater *in-situ* remediation equipment, this control system plays a crucial role in monitoring the operational status of on-site equipment and tracking the progress of groundwater remediation to ensure a smooth process and achieve optimal results. To accomplish this, the control system must have the following key functions:

1) Data Management: The system records operational parameters of remediation equipment and various data from the groundwater wells, storing historical data for easy access and analysis by researchers. This data supports future groundwater pollution remediation efforts, enabling the development of tailored treatment strategies for different contaminated sites, thereby facilitating the swift and efficient cleanup of polluted areas.

2) Human-Machine Interaction: In modern industrial settings, human-machine interaction is an indispensable component of control systems. It translates internal information into formats that are easily understandable and accessible to humans. On-site operators can observe real-time operational status and trends in groundwater quality, such as water level, pressure, and dissolved oxygen concentration. With the help of upper-level software, operators can control equipment based on real-time data trends, such as start-stop operations and pump flow adjustments, as illustrated in Figure 1.

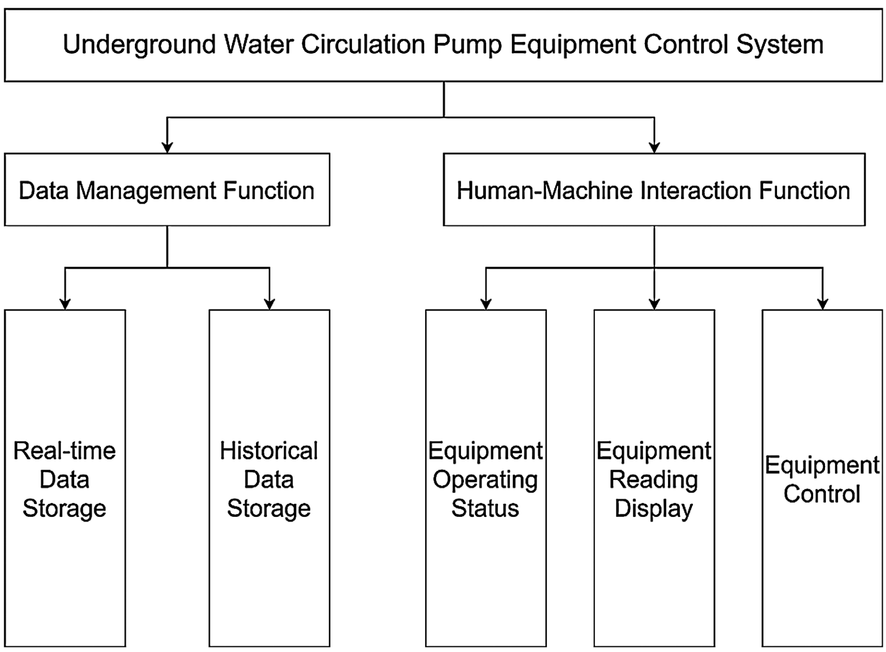

Figure 1. Functional composition structure diagram.

2.3. Design Concept

The software development approach, as shown in Figure 2, consists of four main components: the field device layer, the communication and interconnection subsystem layer, the database platform layer, and the application software end.

At the field device layer, various sensors, pumps, and video monitoring equipment are used in the groundwater pollution remediation site. Data from these devices is uploaded to the on-site industrial control computer's database layer via traditional serial ports using the Modbus protocol.

Subsequently, through node configuration, the data undergoes basic processing, including handling missing values, outliers, and duplicate data to ensure accuracy and consistency [8]. Additionally, the data format is standardized to

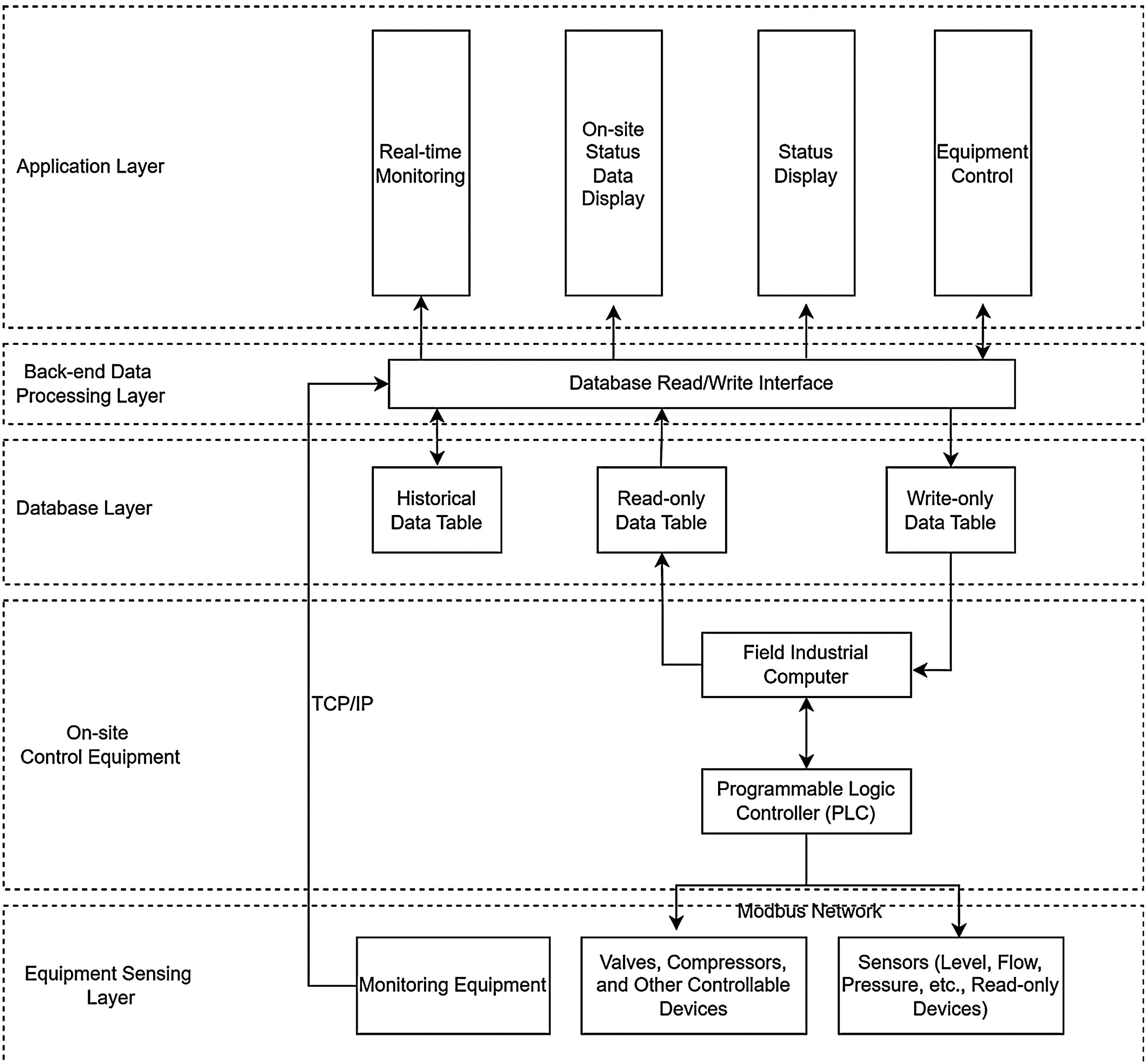

Figure 2. Framework diagram of complete equipment control system.

facilitate better splitting and usage during subsequent storage. The data is transmitted to the network layer using the Modbus TCP protocol and is ultimately stored in a MySQL database [9].

By deploying cloud servers, the data in the database is presented in forms such as charts, enabling more intuitive visualization and making the data easier to understand. This architecture allows the entire system to monitor and display the status of the groundwater remediation site in real-time, thereby achieving effective data management and operation.

2.4. Design of Device Perception Module

The system's sensing modules are categorized into three types:

1) Read-Only Modules: These include devices such as level meters, flow meters, and pressure gauges. They are responsible for reading the status of the site and transmitting the collected data to the PLC using the ModBus protocol via the on-site network.

2) Control Modules: These modules include devices such as valves and pumps. They not only send their current operational status to the PLC but also receive control commands from the PLC during on-site or remote operations. When the control unit issues an operational command, these modules execute the corresponding actions, thereby completing the control tasks of the process.

3) Monitor Modules: These modules bypass the on-site PLC and connect directly to the backend using the TCP/IP protocol. When the front-end visualization port needs to check the site's monitoring status, it can receive real-time status information through the interface program.

This categorization of sensing modules allows the system to collect, transmit, and control on-site data and status as needed, meeting diverse sensing and control requirements [10].

2.5. Design of On-Site Control Equipment Module

Given the variability and often remote locations of groundwater circulation well remediation sites, we have developed a mobile control platform housed within a shipping container. This platform supports the modular development of groundwater pollution remediation equipment, allowing for the entire control system to be easily transported and reused across different sites. The mobile platform plays a critical role in the remediation process, as it enables the system's mobility and enhances its reusability by facilitating site changes.

The control platform consists of two main components: the industrial control computer (IPC) module and the power module.

Once the on-site equipment is installed, a wired ModBus network is established. All field devices transmit their data to the on-site IPC via wired connections. The IPC is equipped with a configuration system to directly control the equipment on-site and creates a local database for storing site data, which is then synchronized with the cloud database. This local database can also receive commands from the cloud database for data synchronization and on-site equipment control. This system architecture ensures effective control and data management of on-site equipment.

The power module is primarily composed of a rooftop solar photovoltaic system, a WiFi wireless system, a micro-weather station, and an on-site power supply system, as illustrated in Figure 3.

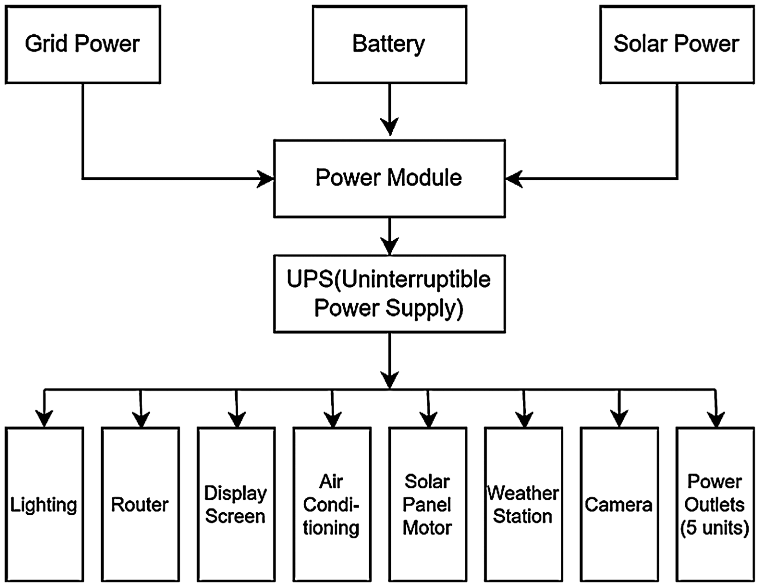

Figure 3. Power module structure diagram.

The solar power system serves as a backup power source within the control platform, providing single-phase power supply to the container interior and control cabinet, but not participating in the external three-phase load power supply. The system uses four 500-watt solar panels, with the battery storage cabinet consisting of eight 12 V 120 Ah batteries. The inverter can be configured to different power supply modes, including grid priority mode and solar priority mode.

The distribution box is a low-voltage distribution device used for 380 V and 220 V electrical distribution. It mainly supplies power to three-phase motors and other electrical equipment at the remediation site. After connecting to an external three-phase power supply, the system routes the power through a leakage protection circuit breaker before it reaches the equipment, preventing electrical faults such as leakage, short circuits, and overloads that could cause personal injury or equipment damage.

The external power supply connects through the main circuit breaker to a current transformer and an energy meter, providing information on the total power consumption of the power module. The energy meter also supports Modbus RTU communication, allowing real-time monitoring of various parameters and power consumption trends through communication with the upper-level computer.

2.6. Database Layer Design

MySQL is an open-source relational database management system that uses tables to store data, supports multi-user access, and provides full SQL functionality. It can run on various operating systems and offers a range of storage engine options. MySQL is widely used in numerous applications and websites, focusing on data security and scalability, with strong community support [11].

In this system, two types of tables will be established in the MySQL database: one for the PLC to write data to MySQL and another for MySQL to transmit control data to the PLC. These tables contain key fields such as device ID, modification time, parameter values, and location. By storing data separately, these tables facilitate future verification of operation completion. By comparing time and data changes, we can determine whether the tables match and thus confirm if the operation has been completed.

When data is synchronized from the industrial control computer's database to the MySQL database, it is stored in the table designed for the PLC to write data to MySQL. The primary function of this table is to synchronize and save real-time data and maintain records. The data required for the visualization page is primarily accessed from this type of table. In the visualization interface, we restore the working status of the site by accessing the latest data from this table in real-time. Additionally, when historical data queries are needed, we can access the database using field names such as time to obtain the required historical data.

When our backend control program needs to send control commands to the on-site PLC, the control command data is written into the PLC control data table in the MySQL database. A trigger in this table sends the modified data to the industrial control computer's database when there is a data change, prompting the PLC to execute the control instructions. This process can be viewed as a master-slave command transmission. Once the PLC completes the control operation, its status is updated. Subsequently, the industrial control computer updates the data and synchronizes the changes to the PLC control data table in the MySQL database. The backend program reads and updates this data in real-time and then pushes it to the front end for display in the visualization interface. This way, the entire control process forms a closed loop. The overall architecture of the database layer is shown in **Figure 4**.

2.7. Design of Backend Data Processing Layer

Given that the local groundwater equipment will be deployed at multiple locations and several sets of equipment will operate simultaneously, we have opted to develop a backend program specifically for handling requests from the visualization interface and database operations, rather than allowing the front-end visualization to directly access the database. This architecture facilitates better management and maintenance of equipment data, while providing a more efficient method for data interaction and display.

The backend interface program is developed in Golang. Its design goals are to enhance development efficiency and code readability while maintaining high performance and reliability. The primary requirements of this backend interface program include CRUD operations on the database, connecting to the front-end

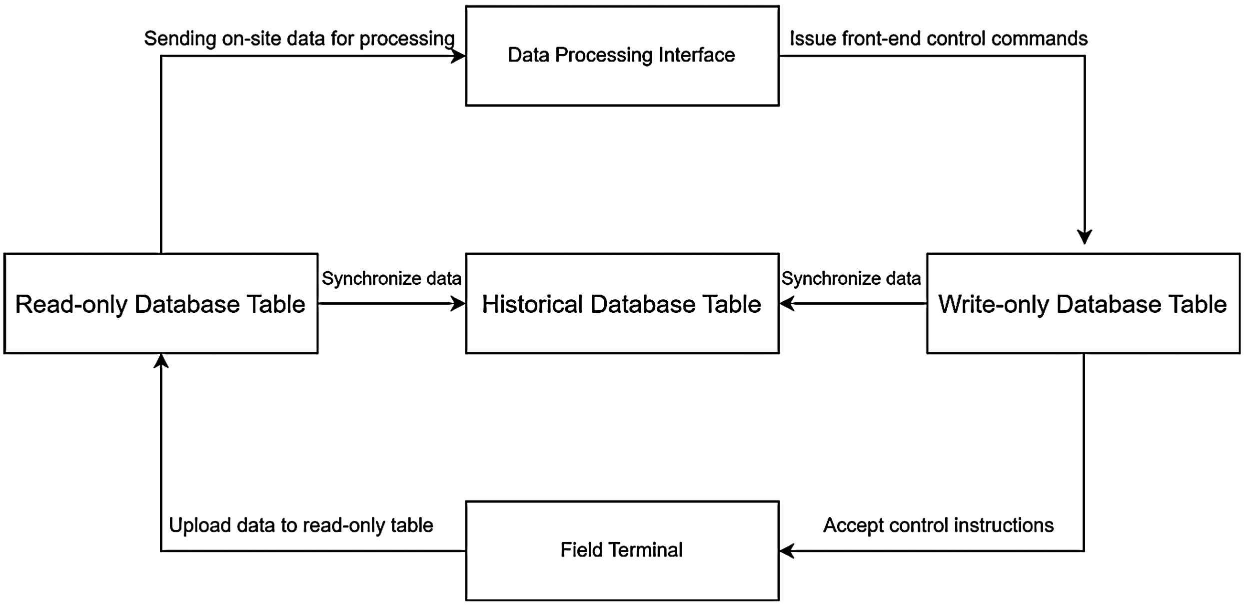

Figure 4. Overall architecture of the database layer.

visualization interface to push messages to the front end, and receiving control messages from the visualization interface.

To meet these requirements, it is essential to establish a communication channel between the program and the front end. This system utilizes WebSocket communication because WebSocket supports persistent, bidirectional communication and allows the server to send messages to the client without requiring a client-initiated request [12]. As the number of equipment sets increases, this communication method can push relevant data to the front end more quickly and effectively.

To accurately display the equipment's operational status in the visualization interface, the backend program implements a timed push method. The interface program queries the PLC-to-MySQL table in the MySQL database every second to obtain the latest operating status of the equipment based on the time field. The queried data is then stored in the local server cache and formatted. Finally, the backend program packages the processed data into JSON format and pushes it to the front end for display. This design ensures accurate display of the equipment's operational status and optimizes data transmission efficiency.

When control operations are performed in the visualization interface, the front end can send control messages directly to the backend via the WebSocket protocol. Upon receiving the data, the backend first stores it in the local cache, then compares it with the MySQL-to-PLC control table in the MySQL database. The data is then converted into the appropriate fields and formats and stored in this table to fulfill the PLC control request. The design framework of the backend data processing layer is shown in **Figure 5**.

2.8. Application Visualization Layer Design

The Groundwater Circulation Well Monitoring and Remediation Visualization

System utilizes Vue as the application platform and is written in JavaScript. Its functionalities are primarily divided into configuration control and status monitoring.

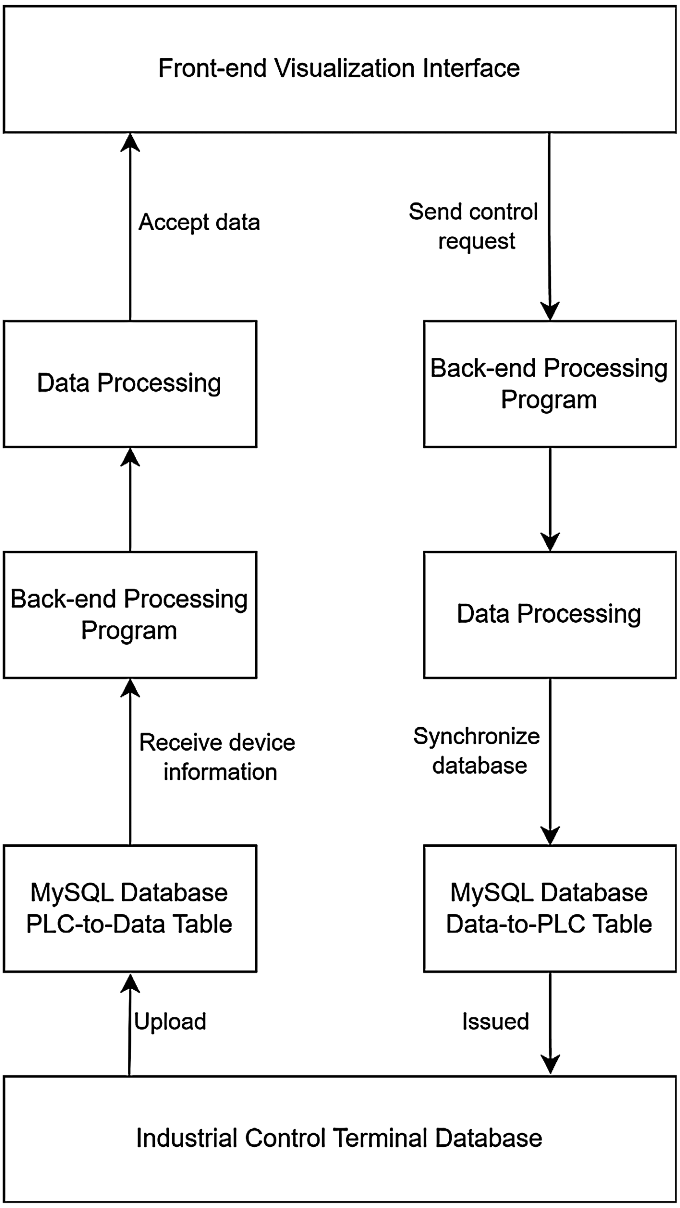

Figure 5. Design framework for backend data processing layer.

As the human-machine interaction interface, the main task of the Groundwater Circulation Well Monitoring and Remediation Visualization System is to monitor the operation of subsystems during the operation of the water circulation well, provide alarms for special situations, and control the operation of remote systems. The system framework designed in this paper is shown in **Figure 6**.

1) Information Processing Layer: This layer operates the database through the backend interface, providing services for front-end users related to main well

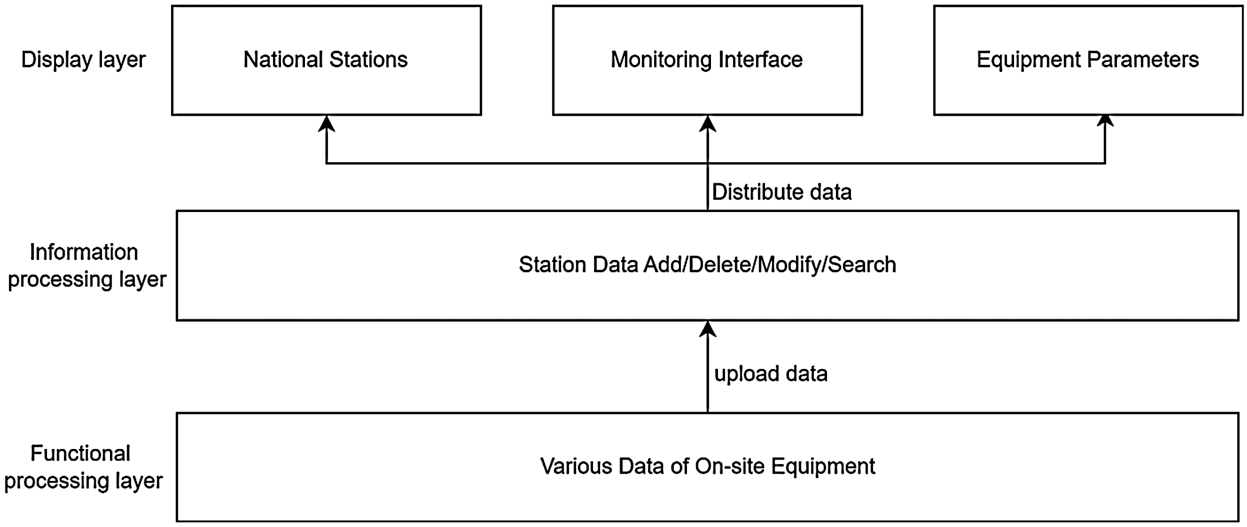

Figure 6. Application visualization layer design framework.

water quality, pump operation, geographic environment, and business control data. It saves this information using Vue's storage tools and supplies page data to the display layer.

2) Function Processing Layer: It uploads information from groundwater circulation well sites across the country and develops programs to operate the data of these sites. This functionality is returned to the backend interface to achieve interaction between the upper and lower layers and serves as the core logic for system control.

3) Display Layer: This layer displays the data stored in Vue's storage tools, including nationwide data on the homepage, site monitoring screens, and various data on equipment operation parameters. It also provides control over the water circulation wells.

The front-end design of the Vue platform involves three languages: HTML, CSS, and Vue. The homepage of the platform provides an overview of all groundwater circulation well remediation sites nationwide and is divided into three parts: the header, content, and footer. The header displays content prompts for the page, while the content section shows the location of each site on a map along with their operational status and any warning data. The footer contains the website's menu bar, which includes Site Management, Equipment Management, Data Reporting, Queries, Remediation Effect, and System Settings. Site Management serves as the core business layer of the website, allowing users to add, delete, modify, and query monitoring data for each site.

System control is implemented through web configuration. Web configuration primarily uses CSS to create digital representations of on-site equipment, pipelines, and process flows, providing a more intuitive display of equipment status and working principles.

The main control method involves clicking switches and invoking corresponding button methods. Once the front end receives a click event, it translates this information into a specific format and sends it to the backend program via the WebSocket protocol. Upon receiving the information, the backend program communicates with the database to achieve synchronized control of on-site equipment. System monitoring is conducted by the backend program, which uses WebSocket communication to push processed JSON data to the front end at regular intervals.

After the front end receives all the JSON data required for system monitoring, it visualizes the data directly based on the display components' binding methods, presenting the on-site conditions. Each display component can access the necessary data directly from the cache, providing the current component with the required information. By using Vue's interpolation expressions for dynamic data binding, real-time display of monitoring data is achieved. For data that requires monitoring and alarms, comparison methods and threshold settings are implemented. When data exceeds these thresholds, the homepage displays an alert for the site, thus realizing monitoring and alarm functionality [13].

3. Implementation of Configuration Control System

The hardware component of the system has been successfully deployed at an experimental site at Chang'an University. This system consists of a movable control platform, a main well, an aeration well, a dosing well, and eleven monitoring wells. The wells are strategically arranged at fixed positions, each equipped with relevant sensors. These sensors are connected to the program located on the movable control platform, allowing the program to obtain real-time data from all sensors.

The main well is designed to guide the flow of groundwater at a fixed location, ensuring that the injected chemicals and other agents are evenly distributed across all areas. The dosing well is responsible for controlling the delivery of chemicals, while the aeration well facilitates thorough contact between groundwater and air. All control devices are connected to the program on the movable control platform via wired or network communication, enabling real-time execution and control of equipment operations, as shown in **Figure 7**.

The main well has two operational states. Among the three pipes located underground, one pipe connected to an air compressor is responsible for inflating the middle diaphragm, thereby separating groundwater at two different depths. The other four pipes manage water intake and discharge. By controlling the valve positions, the system can perform either low-level intake with high-level discharge or high-level intake with low-level discharge. This creates a circulation of groundwater through the screens on both sides of the pipes, achieving the effect of *in-situ* remediation.

Since the on-site system continuously sends data to the database in real-time, when we open the software from a remote device, it automatically accesses the database to read and display the data. If the software detects that a site has data being updated continuously, it will display detailed information about that site.

To view the *in-situ* groundwater remediation data for a specific site, simply click on the corresponding site icon in the software interface to access the site's data page. At this point, the software will access the database in real-time to retrieve the on-site data. Not only will the data in the charts be updated in real-time, but the replicated scene diagram will also dynamically display the operational status of the site based on the database data, including water flow direction, valve positions, and more. The results are shown in Figure 8.

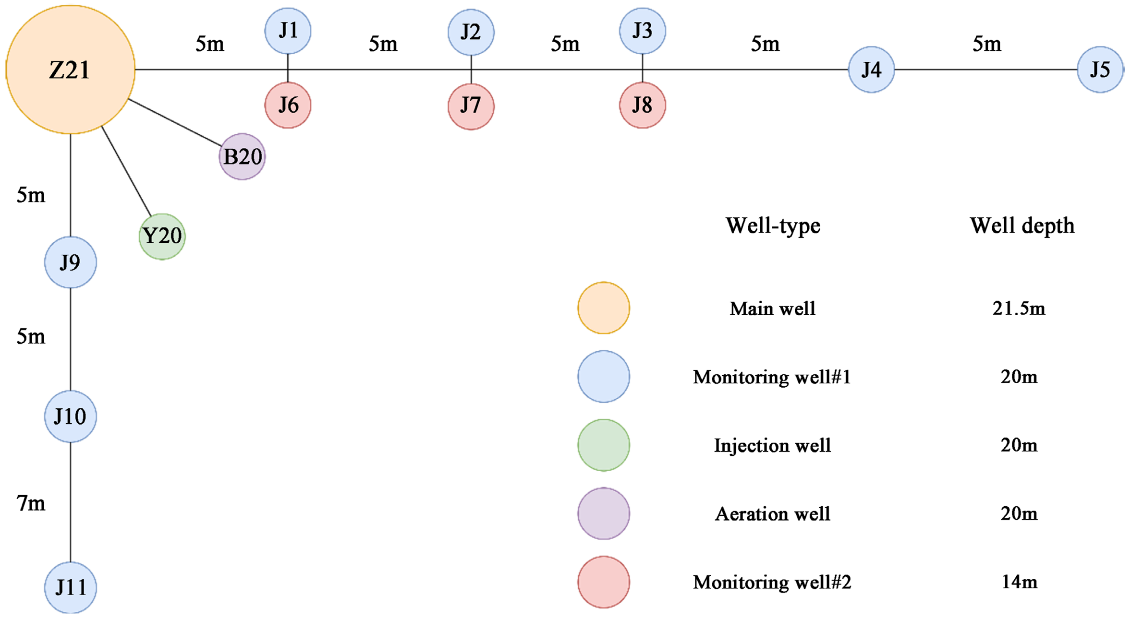

Figure 7. Groundwater well location distribution map.

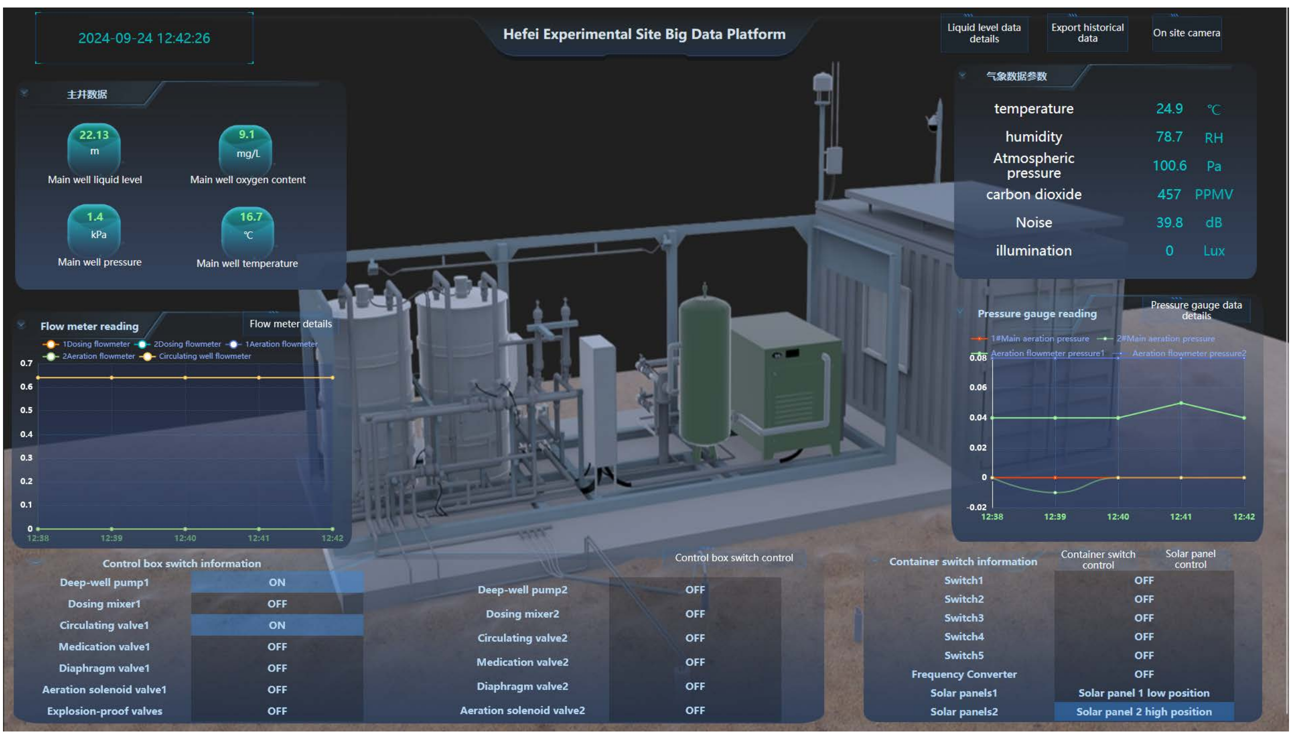

Figure 8. Schematic diagram of configuration control page.

1) When comparing the display data in the configuration diagram with the database data and on-site data, it was found that the front-end page displays normally and smoothly.

2) When controlling the equipment on-site and comparing it with the database and display page, both the database and display page accurately updated the on-site status values within 1 second.

3) When clicking the on-site monitoring video button on the configuration page, a video display window quickly popped up, accurately showing the on-site monitoring status.

4) When initiating control commands on the configuration page and comparing them with the database and on-site equipment, it was found that both the database and the on-site equipment accurately received the command values and performed actions within 1 second.

In summary, by comparing the data displayed on the configuration diagram, the database data, and the on-site data, we found that the system performs well. The frontend page displays normally and smoothly, and on-site control operations and data updates are accurately synchronized within one second, ensuring real-time performance and reliability. The on-site monitoring video feature on the configuration page quickly pops up a video display window and accurately shows the on-site status. The initiation and execution of control commands also demonstrate the system's efficiency, with both the database and on-site equipment responding to commands and performing actions within one second. After multiple practical tests and monitoring, the system has shown stable performance without any lag or anomalies, effectively achieving on-site monitoring, control, and visualization, and meeting the software design requirements.

4. Conclusion

1) This paper successfully constructs a groundwater *in-situ* remediation circulation well control system using web configuration technology, enabling the display of on-site configuration screens and data on a web interface, as well as remote control of on-site equipment. Compared to traditional industrial control methods, this software achieves monitoring from a distance by deploying remotely on the cloud, making the monitoring process safer, more reliable, and more convenient. This design not only offers convenience and practicality but also provides greater flexibility, offering more possibilities for on-site operations.

2) The system utilizes cloud servers and cloud-based real-time historical data to store the massive amounts of data generated by the long-term operation of the circulation well system. This foundation supports better solutions for groundwater pollution issues through big data analysis and deep learning techniques in the future.

Fund Project

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Conflicts of Interest

The authors declare no conflicts of interest.

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